Theoretical Radii of Transiting Giant Planets: The Case of OGLE-TR-56b

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ABSTRACT

We calculate radius versus age trajectories for the photometrically-selected transiting extrasolar giant planet, OGLE-TR-56b, and find agreement between theory and observation, without introducing an ad hoc extra source of heat in its core. The fact that the radius of HD209458b seems larger than the radii of the recently discovered OGLE family of extremely close-in transiting planets suggests that HD209458b is anomalous. Nevertheless, our good fit to OGLE-TR-56b bolsters the notion that the generic dependence of transit radii on stellar irradiation, mass, and age is, to within error bars, now quantitatively understood.

Subject headings: stars: individual (OGLE-TR-56b)—(stars:) planetary systems—planets and satellites: general

1. Introduction

The measurement of the Doppler wobble of more than 120 nearby stars induced by the presence of a planetary-mass companion has revealed a population of extrasolar giant planets (EGPs) that is the focus of an increasing fraction of the world's astronomers [1]. However, due to the fact that for the vast majority of these EGPs the orbital inclination (i) is not known, only a lower limit, the projected mass ($M_p \sin(i)$), constrains the actual planetary mass (M_p). Though the orbital distances (a), periods (P), and eccentricities (e) are well

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[1]see J. Schneider's Extrasolar Planet Encyclopaedia at http://www.obspm.fr/encycl/encycl.html and the Carnegie/California compilation at http://exoplanets.org for current tallies and the associated stellar data.

determined, to study an EGP in physical detail requires physical information, such as the actual mass, the radius, and the spectrum.

The detection of planetary transits across the face of the parent star provides the first two of these desiderata and with both masses and radii the structural (and to some degree compositional) character of the EGP can be studied (Guillot et al. 1996). HD209458b was the first EGP to be detected to transit its primary (Henry et al. 2000; Charbonneau et al. 2000) and at a distance of only $\sim$47 pc, it is bright enough to yield (using HST/STIS) a transit light curve with $\sim$100-*micro*magnitude precision (Brown et al. 2001). Proximity also enables precise radial velocity measurements. As a consequence, the data for this radial-velocity-selected transiting EGP are some of the best we can expect (Brown et al. 2001; Mazeh et al. 2000; Cody & Sasselov 2002). Furthermore, the overall transit probability for an EGP in the Doppler surveys is very roughly 0.1 (fraction close enough) $\times$ 0.1 (fraction near 90° inclination) = 0.01. Since of order 100 EGPs have been detected, and the Doppler surveys of nearby stars are approaching completeness, we can't expect too many more like HD209458b.

It is in this context that the photometrically-selected transiting EGPs OGLE-TR-56b (Konacki et al. 2003; Sasselov 2003; Torres et al. 2004), OGLE-TR-113b (Bouchy et al. 2004; Konacki et al. 2004), and OGLE-TR-132b (Bouchy et al. 2004) should be viewed. The small subset of the stars in the OGLE galactic survey that show periodic photometric dips, but that also survive close scrutiny for false positives (stellar binarity, confusion, etc.), has the potential to add considerably to our knowledge of the Radius-Mass relation for EGPs. Table 1 gives relevant stellar and planetary data for the known transiting systems, along with associated references.

However, at distances of perhaps 1500 pc, even 8-meter class telescopes can't provide the level of Doppler precision necessary to compete on a regular basis with that achievable by the ongoing radial-velocity surveys in the solar neighborhood. Moreover, at a distance of $\sim$1500 pc, an accurate measurement of the depth of the photometric transit is a major challenge. Nevertheless, the large volume surveyed by the OGLE team, and the large volumes that can be surveyed using similar photometric approaches, imply that such programs have the potential to yield a rich harvest of transiting EGPs. Ground-based photometric transit surveys will pave the way for the more precise space-based surveys to be conducted by Kepler (Koch et al. 1998) and COROT (Antonello & Ruiz 2002). Therefore, we can expect in the years to come a large family of EGPs for which both radii and masses are known and, hence, for which a robust theory of EGP radii will be required.

Theories for the radius of HD209458b in particular (Burrows et al. 2000; Hubbard et al. 2001; Fortney et al. 2003; Burrows, Sudarsky, & Hubbard 2003; Bodenheimer, Lin,

& Mardling 2001; Bodenheimer, Laughlin, & Lin 2003; Guillot & Showman 2002; Showman & Guillot 2002; Allard et al. 2003; Baraffe et al. 2003) and for irradiated EGPs ("roasters") in general (Guillot et al. 1996; Burrows, Sudarsky, & Hubbard 2003; Baraffe et al. 2003; Chabrier et al. 2004) are appearing that address many of the issues that surround theoretical calculations of the radii of irradiated EGPs and their evolution. We refer to the discussion in Burrows, Sudarsky, & Hubbard (2003, BSH) for a critique of the literature and a summary of the various methods.

The apparent anomaly of the OGLE transits is the small inferred transit radii in the optical (Table 1), given the larger measured radius for HD209458b. Since the orbital distance of OGLE-TR-56b in particular is half (0.0225 AU) that of HD209458b (0.045 AU), it might have been expected that the greater stellar insolation would have "expanded" its radius even more than that of HD209458b. To explain the large radius of HD209458b, a number of theorists have invoked an additional heat/power source in the core, due either to the conversion of a fraction of the intercepted stellar light into deeply-penetrating mechanical waves (Baraffe et al. 2003; Guillot & Showman 2002; Showman & Guillot 2002), or to the presence of an as-yet-unseen companion that induces a slight eccentricity in HD209458b (Bodenheimer, Laughlin, & Lin 2003). Such an eccentricity can result in tidal heating. Chabrier et al. (2004) have calculated models for OGLE-TR-56b, but have suggested that the injection of added power might be needed to compensate for what would otherwise be a $\sim$0.1 R_J [2] discrepancy between their determination and the central value of the measured transit radius. However, their numbers do clip the lower end of the error bar range. In this paper, our goal is to explain the measured radius of OGLE-TR-56b using the tools and approximations described in BSH, without invoking any additional heat source. We find that the radius of OGLE-TR-56b can indeed be fitted comfortably using this theory.

In §2, we summarize our approximations and approach. In §3, we present our theoretical results for the evolution with age of the radius (R_p) of the transiting planet OGLE-TR-56b and compare theory with observation. In §4, we review our conclusions and attempt to put them, as well as our physical theory, into the broader context of the family of irradiated EGPs, both those that are known and those to be discovered. We end with a synopsis of the improvements in the theory of irradiated EGPs that are necessary to make further progress.

[2] $R_J = 7.149 \times 10^4$ km, Jupiter's radius

2. Techniques and Physically-Motivated Assumptions

The evolution of an EGP in isolation requires an outer boundary condition that connects radiative losses, gravity (g), and core entropy (S). In this case, the radiative losses are given by $4\pi R_p^2 \sigma T_{eff}^4$, where $T_{\rm eff}$ is the effective temperature, R_p is the planet's radius, and σ is the Stefan-Boltzmann constant. When there is no irradiation, the effective temperature determines both the flux from the core and from the entire object. A grid of $T_{\rm eff}$, g, and S, derived from detailed atmosphere calculations, can then be used to evolve the EGP (Burrows et al. 1997).

Stellar irradiation can drastically alter an EGP's atmosphere and the relationship between the core entropy, gravity, and core luminosity. The latter can be tied to an effective temperature ($T_{\rm eff}$), but this is now very much lower than the equilibrium temperature (Sudarsky, Burrows, and Hubeny 2003) achieved in the roaster's upper atmosphere. It is this $T_{\rm eff}$ that determines the rate with which the irradiated planet's core cools (BSH) and it is the core entropy that dominates the determination of the radius of a planet of a given mass. Hence, when there is stellar irradiation, $T_{\rm eff}$ gives the flux from the core and determines the inner boundary condition for the atmosphere problem, but does not determine the total emergent flux. This is given by the sum of the irradiation flux and core flux. As a result, a more careful atmosphere calculation, one that penetrates deeply into the convective zone to Rosseland optical depths of $\sim 10^6$ and pressures of $\sim 10^3$ bars, is required to establish the boundary conditions necessary for evolutionary calculations of severely irradiated EGPs. We use a specific variant of the stellar atmosphere code TLUSTY (Hubeny 1988; Hubeny and Lanz 1995), called COOLTLUSTY (briefly described in Sudarsky, Burrows, Hubeny 2003), to calculate T/P profiles and evolutionary boundary conditions for irradiated EGPs such as OGLE-TR-56b, the evolutionary code of Burrows et al. (1997), the H/He equation of state of Saumon, Chabrier, & Van Horn (1995), the opacity library described in Burrows et al. (2001), an updated version of the thermochemical database of Burrows & Sharp (1999), and a stellar spectrum for OGLE-TR-56 (with an assumed spectral type of G2 V) from Kurucz (1994).

As BSH have shown, the transit radius is not the standard "1-bar" pressure radius (Lindal et al. 1981), nor the "$\tau = 2/3$" photospheric radius. It is the radius at which the optical depth (at a given frequency) along the chord perpendicular to the radius vector is of order unity. As a result, the ratio of the photospheric pressure to the "transit pressure" is near $(2\pi\ R_p/H)^{1/2}$, where H is the pressure scale height (Smith & Hunten 1990). This adds $\sim$5 pressure scale heights to the $\sim$10 pressure scale heights between the canonical photosphere and the radiative/convective boundary. As found in BSH, the upshot for HD209458b is an increase of $\sim$10% in its transit radius. For this paper, we have calculated the transit pressure

for OGLE-TR-56b using the methodology of Fortney et al. (2003) and find an average value in the optical of ∼20 to 30 millibars for $f = 0.5$ and $f = 0.25$, respectively. This translates into an increase of ∼3-4.5% in the transit radius of the more massive OGLE-TR-56b.

To carry out calculations of the evolution of R_p with age for a given M_p and irradiation regime, we must assume a helium fraction (Y_{He}), address the issue of the possible presence of a rocky core, account for variations in the angle of incidence of the stellar radiation across the planet's surface, and address the issue of the difference between the day- and night-side cooling. For these calculations, we take $Y_{He} = 0.30$. This is larger than the Y_{He} expected, but can account for the effect of a rocky core. As shown by BSH for HD209458b, a 10-Earth-mass core shrinks the planet by only ∼3-4%. This is similar to the effect of increasing Y_{He} by 0.02. For the more massive OGLE-TR-56b (Table 1), the effect of a rocky core is smaller still. As described in BSH, we have introduced the flux parameter f which accounts in approximate fashion for the variation in incident flux with latitude when using a planar atmosphere code. A value of $f = 1/2$ assumes that there is little sharing of heat between the day and night sides. A value of $f = 1/4$ assumes that in the calculation of the T/P profile the heat from irradiation is uniformly distributed over the entire sphere. In this paper, we show the results for both assumptions, but favor $f = 1/4$ to approximately account for what may be significant redistribution to the night side.

The issue of the value of f is tightly coupled to the day-night cooling difference. The $T_{\rm eff}$ for the core in each hemisphere depends upon the strong atmospheric circulation currents that advect heat from the day to the night sides (BSH; Guillot & Showman 2002; Showman & Guillot 2002; Menou et al. 2002; Cho et al. 2003; Burkert et al. 2004). A three-dimensional radiation/hydrodynamic study or Global-Climate-Model (GCM) is beyond the scope of this paper. In lieu of that, we assume as in BSH and as do Baraffe et al. (2003) that the flux from the core in both hemispheres is the same. This does not mean that the T/P profiles are the same at altitude, only that the flux at depth at the radiative/convective boundary is the same.

3. Results for OGLE-TR-56b: R_p versus Age

Figure 1 depicts evolutionary trajectories of the transit radius R_p in the optical versus age for the $f = 1/2$ and $f = 1/4$ models of OGLE-TR-56b (gold). For both models, $Y_{He} = 0.30$ and $M_p = 1.45\ M_J$. Included is the corresponding trajectory for an isolated planet with OGLE-TR-56b's characteristics. Irradiation is seen to increase R_p by ∼0.2-0.3 R_J, depending upon age and f. We have used the theory of Fortney et al. (2003) with our derived T/P and optical depth profiles to calculate a transit pressure level and, hence, the

magnitude of the "impact parameter" that is the transit radius. Despite the larger insolation flux, OGLE-TR-56b's larger gravity results in a slightly smaller "atmospheric thickness" effect (3-4.5%) than for HD209458b (∼10%). Superposed on Fig. 1 are the OGLE-TR-56b data from Table 1, where the age of OGLE-TR-56b is ascribed to Sasselov (2003). For comparison, Fig. 1 includes two representative models (black) from BSH for the evolution of HD209458b's transit radius, with $Y_{He} = \{0.25, 0.30\}$ and $f = 1/2$. The age and R_p estimates for HD208458b listed in Table 1 are plotted. The lowest 1-σ error bar for HD209458b is from Cody & Sasselov (2002), under the assumption that the lower estimate of the corresponding stellar radius (∼1.1 $R_\odot$) obtains (BSH).

As Fig. 1 indicates, our theoretical curves are quite consistent with the OGLE-TR-56b data. The higher f gives larger R_p, but by only $\lesssim$4% after a Gigayear (Gyr). At a young age of 10^8 years, R_p can be near 1.5 R_J , but it is ∼1.2-1.25 R_J after 2 Gyrs. We have calculated trajectories (not shown) for the OGLE-TR-56b irradiation regime, but for M_p= 1.68 M_J and 1.22 M_J . After $\sim 3 \times 10^8$ years, they are within less than 1% of that for M_p= 1.45 M_J . R_p is a very weak function of planet mass, reflecting the general "$n = 1$" polytropic character of EGPs (Burrows et al. 1997; Burrows et al. 2001). Even if M_p for OGLE-TR-56b were 0.7 M_J , R_p would be larger by only ∼0.05 R_J or ∼0.1 R_J for ages of 3 Gyr and 0.1 Gyr, respectively. On Fig. 1, the small black arrow on the right indicates the effect of a 10 Earth-mass rocky core on models for HD209458b. For OGLE-TR-56b, at twice the mass and ∼2.5 times the gravity, the arrow would be less than half as long. The weak dependence on age, M_p, Y_{He}, and the possible presence of a rocky core implies that we have in our calculations incorporated the essential physics, chemistry, and radiative effects necessary to explain the transit radius of OGLE-TR-56b, without invoking an added power source in the core. The major effects are the stanching of core cooling (and the decrease in $T_{\rm eff}$) by irradiation's effect on the atmospheric T/P profile (Burrows et al. 2000; BSH) and the 0.04-0.05 R_J difference due to the proper definition of the transit radius (BSH; Baraffe et al. 2003). For OGLE-TR-56b, the pressure at the radiative/convective boundary is between 600 and 900 bars, depending upon true age and f. This is slightly lower than that for HD209458b, reflecting the larger mass. The rate with which the radiative front is now penetrating OGLE-TR-56b is ∼200 bars per Gyr, equivalent to a scant $\sim 3 \times 10^{-5}$ M_J per Gyr.

4. Conclusions

We have shown that our theory, which couples spectral, atmospheric, and evolutionary calculations in a straightforward manner, can explain the measured transit radius of OGLE-

TR-56b. Our calculations yield values for R_p that are $\sim$0.1 R_J higher than those of Chabrier et al. (2004), which without an extra heat source undershoot by $\sim$10% the central value of the OGLE-TR-56b R_p measurement. Since they are using a similarly sophisticated approach, the source of this difference is unknown.

The larger radius of HD209458b is still problematic, but even it can be fitted without an ad hoc extra power source, if its true transit radius is at the lower end of the measured range (BSH). It is important to remember that systematic errors still dominate estimates of R_p. Furthermore, not only is OGLE-TR-56b smaller than HD209458b, but so too seem OGLE-113b and OGLE-132b (however, note the large error bars in Table 1). Curiously, all the OGLE roasters have smaller orbital distances. This implies that HD209458b is the anomaly, perhaps due to tidal heating caused by an as-yet-unseen second companion (Bodenheimer, Laughlin, & Lin 2003) or to residual systematic errors. Hence, a compelling argument can be made that the transit radii of all the OGLE EGPs are consistent with a model that does not require any extra heating term beyond that supplied quite naturally through the standard effects of irradiation and radiative transfer into the convective core.

The remaining theoretical uncertainties are the actual day-night cooling differences, the 3D effects of atmospheric circulation and zonal heat transport, and the early history of the planet. As shown by Burrows et al. (2000), and as is implied on Fig. 1, if the EGP were born at large orbital distances, but took more than $\sim 3 \times 10^7$ years to migrate in to its present distance, then its radius would have shrunk below a value consistent with the measured R_p (for any of the objects listed in Table 1). One could then accommodate an extra heat source, since it would be needed to compensate for the early loss of core entropy. However, such a migration time is deemed rather long, and we prefer to shave with Occam's Razor.

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Table 1. Data for Current List of Transiting EGPs

EGP	M_* ($M_\odot$)	R_* ($R_\odot$)	a (AU)	P (days)	M_p (M_J)	R_p (R_J)	Age
HD209458b[1]	1.1 ± 0.1	1.2 ± 0.1	0.045	3.525	0.69 ± 0.05	1.4 ± 0.17	$5.5 \pm$
HD209458b[2]	1.06 ± 0.1	1.18 ± 0.1	0.045	3.525	0.69 ± 0.02	$1.42^{+0.12}_{-0.13}$	$5.2 \pm$
HD209458b[3]	1.1 ± 0.1	1.146 ± 0.05	0.045	3.525	~ 0.69	1.347 ± 0.06	-
OGLE-TR-56b[4]	1.04 ± 0.05	1.1 ± 0.1	0.0225	1.212	1.45 ± 0.23	1.23 ± 0.16	$2.5^{+1.}_{-1.}$
OGLE-TR-113b[6]	0.77 ± 0.06	0.765 ± 0.025	0.0228	1.433	1.35 ± 0.22	$1.08^{+0.07}_{-0.05}$	-
OGLE-TR-113b[7]	0.79 ± 0.06	0.78 ± 0.06	0.023	1.432	1.08 ± 0.28	1.09 ± 0.10	-
OGLE-TR-132b[6]	1.34 ± 0.1	$1.41^{+0.49}_{-0.10}$	0.0306	1.689	1.01 ± 0.31	$1.15^{+0.80}_{-0.13}$	-

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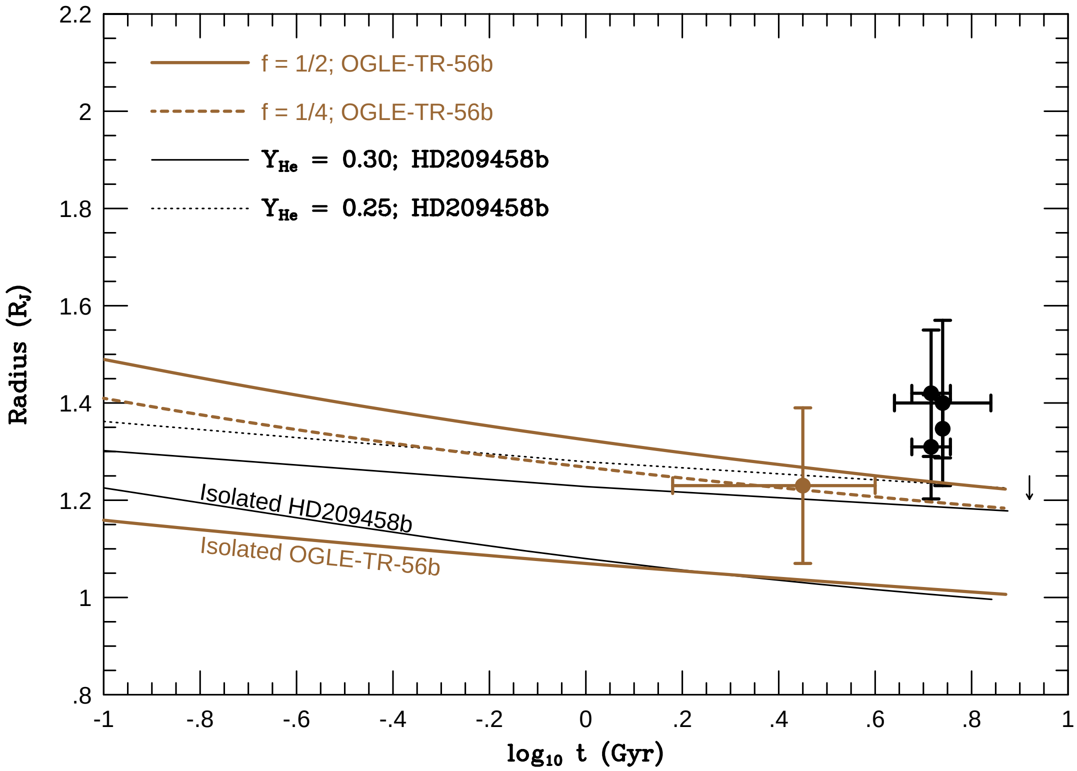

Fig. 1.— Theoretical evolutionary trajectories (in gold) of the optical transit radius of OGLE-TR-56b (in units of R_J) with age (in Gyrs). The effects of irradiation are included. A mass of 1.45 M_J , a helium fraction of 0.30, and values of the insolation parameter f of 1/4 and 1/2 are assumed (see BSH and text for discussion). Model "Isolated OGLE-TR-56b" is for a 1.45 M_J EGP in isolation. The measured optical transit radius and estimated age, accompanied by $\pm 1 - \sigma$ error bars and taken from Torres et al. (2003) and Sasselov (2003), are rendered with the gold cross. For comparison, evolutionary tracks for HD209458b from BSH, assuming helium fractions of 0.25 and 0.30, along with the corresponding age and radius estimates from Mazeh et al. (2000), Brown et al. (2001), and Cody and Sasselov (2002), are plotted (all in black). A model of HD209458b in isolation ("Isolated HD209458b") is also shown. The short arrow to the right of the HD209458b error boxes depicts the magnitude of the radius decrease for each 10 Earth-mass increase in the mass of a possible rocky core in HD209458b. See text for explanations.